

## OPTICAL DEVICE

## BACKGROUND OF THE INVENTION

## Field of the Invention

5        The present invention relates to an optical device which is suitable for use with an optical amplifier or the like in wavelength-division multiplexing (WDM) communication, and which has a variable optical attenuating function or a light-intercepting function.

## Description of the Related Art

10       In WDM communication, multiwavelength signal light of a spectrum band of 1.55  $\mu\text{m}$  emitted from a transmitting station is carried through one optical fiber, and is received by a receiving station, whereby high-capacity optical communication is carried out. In order to correctly receive the multiwavelength signal light at the receiving station, the power of the signal 15       light of each wavelength that reaches the receiving station must substantially be the same. To achieve this requires a variable optical attenuator that

optical amplifier in an optical transmission line with respect to the wavelengths of the signal light.

20       A conventional example of a variable optical attenuator is disclosed in Ref. 1 by Kawai et al. (The Inst. of Electronics, Inf. and Commun. Engineers (IEICE) Communication Society Convention, B-10-61, 1997). As shown in Fig. 1, the variable optical attenuator comprises a substrate 1, a Mach-Zehnder

interferometer 12, and a heater 9 that is disposed on at least one of the arms of the Mach-Zehnder interferometer 12. The Mach-Zehnder interferometer 12 includes an optical circuit that comprises a core and a cladding that covers the core. The variable optical attenuator controls the amount of optical 5 attenuation by adjusting phase differences between the two arms by thermal phase shifting.

The amount of optical attenuation by the variable optical attenuator is required to be equal to or greater than 35 dB, preferably equal to or greater than 40 dB. In the variable optical attenuator that makes use of a Mach-Zehnder interferometer, in order to increase the amount of optical attenuation to such values, two or more of the Mach-Zehnder interferometers 12, shown in 10 Fig. 1, are connected in series (for example, in Japanese Patent Application Laid-Open No. S62-183406).

Further, in the variable optical attenuator in Ref. 1, the heating portion 15 is only at one side of the core. Since the thermal expansion coefficient of the heater and that of the optical circuit are different, when thermal phase

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This increases polarization dependence of optical attenuation, so that optical performance is considerably reduced. For example, a typical polarization 20 dependent loss (PDL) of a commercially available variable optical attenuator of the type disclosed in Ref. 1 is about 0.3 dB when the amount of optical attenuation is 10 dB, and is about 0.7 dB when the amount of optical attenuation is 15 dB. From the system side, a reduction in PDL to a value

equal to or less than 0.2 dB over the entire operating range is expected.

### SUMMARY OF THE INVENTION

It is an object of the present invention to provide an optical device whose  
5 size, power consumption, insertion loss, and polarization dependence are made  
smaller, and which has a variable optical attenuating function or a light-  
intercepting function.

In order to achieve this object, an optical device is provided in which the  
10 optical device comprises a substrate; an optical circuit, including a core and a  
cladding, which is formed on the substrate, the optical circuit which is divided  
into two portions by a groove that traverses the core such that the core being  
divided into two core elements; an optical element having an optical  
attenuating function, the optical element being movably disposed inside the  
15 groove at a location between the core elements; and means for actuating said  
optical element.

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more fully clarified in the following detailed description when the same is read in connection with the accompanying drawing. It is to be expressly understood, however, that the drawing is for the purpose of illustration only and is not intended as a definition of the limits of the invention.

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#### BRIEF DESCRIPTION OF THE DRAWING

Figure 1 is a plan view of a conventional variable optical attenuator.

Figure 2 is a graph showing a typical relationship between the amount of optical attenuation and PDL of the conventional variable optical attenuator.

10 Figures 3A and 3B show an embodiment of an optical device of the present invention, in which Fig. 3A is a plan view and Fig. 3B is a sectional view along line IIIB-IIIB shown in Fig. 3A.

Figure 4 is an enlarged end view of an optical element taken along line IV-IV shown in Fig. 3A.

15 Figures 5A and 5B show another embodiment of an optical device of the present invention, in which Fig. 5A is a plan view and Fig. 5B is a sectional

Figures 6A and 6B show an example of an optical element used in the optical device of the present invention, in which Fig. 6A shows a case where 20 the optical element rotates and Fig. 6B shows a case where the optical element is a lens.

Figure 7 is an enlarged end view of an optical element used in the first example as viewed from a signal-light-incident direction.

Figure 8 shows in detail an actuation function portion used in the first example.

Figure 9 is a graph showing the relationship between the amount of optical attenuation and PDL of the optical device of the first example.

5 Figures 10A and 10B show an optical device of the second example, in which Fig. 10A is a plan view and Fig. 10B is a sectional view taken along line XB-XB shown in Fig. 10A.

10 Figures 11A and 11B show an optical element used in the second example, in which Fig. 11A is a sectional view and Fig. 11B is an end view of

the optical element as viewed from a signal-light-incident direction.

#### DETAILED DESCRIPTION OF THE INVENTION

In the following, preferred embodiments of the present invention will be explained in detail with reference to the accompanying drawings. To facilitate 15 the comprehension of the explanation, the same reference numerals denote the same parts, where possible, throughout the drawings, and a repeated

exaggerated and do not always correspond to actual ratios of dimensions.

Figures 3A and 3B show an embodiment of an optical device of the 20 present invention, in which Fig. 3A is a plan view and Fig. 3B is a sectional view taken along line IIIB-IIIB shown in Fig. 3A. An optical circuit 23 comprising a core 2 and a cladding 3 that covers the core 2 is formed on a substrate 1. A groove 4 which traverses the core 2 is formed across the optical

circuit 23. As far as the groove 4 is formed deeper than a region through which signal light is transmitted, it does not matter whether the groove 4 is structured within the depth of the optical circuit 23 or is sufficiently deep to reach the substrate 1. An optical element 5 which has an optical attenuating function and which is connected to an actuation function portion 6 through a supporting portion 7 is placed inside the groove 4 so as to be movable along the groove 4. The actuation function portion 6 is supported at the sides opposite the supporting portion 7 by securing portions 8 disposed on the optical circuit 23.

10 Figure 4 is an enlarged end view of the optical element 5 as viewed from a direction of line IV-IV. An optical attenuation portion 30, in which optical attenuation elements 30-1 to 30-4 are arranged in a row for providing different amounts of optical attenuation, is disposed on a light-receiving surface 5-1 of the optical element 5 on which signal light is incident. The optical attenuation elements 30-1, 30-2, 30-3, and 30-4 provide optical attenuation amounts of approximately 0 dB, 10 dB, 20 dB, and 40 dB, respectively, for the optical

15 the side of the actuation function portion 6 adjacent to the supporting portion 7 moves along the groove 4, thereby causing the optical element 5 to move inside the groove 4. In this way, the signal light can be discretely attenuated in accordance with the amount of optical attenuation by the optical attenuation elements 30-1 to 30-4, which are interposed between the core elements of the core 2.

The optical attenuation elements 30·1 to 30·4 are formed of dielectric multi-layer films that absorb or reflect a portion of the signal light, or metallic thin films, such as gold, copper, or nickel films. When the transmittance ratios of the optical attenuation elements 30·1 to 30·4 are 100 to 0.01%, the light 5 attenuation amounts can be 0 dB to 40 dB. When dielectric multi-layer films are used, the transmittance ratios of the optical attenuation elements 30·1 to 30·4 can be adjusted by adjusting film refractive indices, film thicknesses, and the number of layers used. On the other hand, when metallic thin films are used, they can be adjusted by adjusting the materials used, the film thicknesses, and the composition ratios.

10 The optical element 5 has a side whose length is approximately 10 to a few 100  $\mu\text{m}$ , a thickness of approximately 10 to 100  $\mu\text{m}$ , and a weight equal to or less than a few 100 mg, so that it is very small and light. Therefore, the driving power of the actuation function portion 6 can be made approximately 15 equal to or less than 0.5 W. The amount of time required to move the optical element 5 can be made to be about 1 ms. The optical device can be made small

which is suitable for integration, and which reduces loss of the optical circuit itself.

20 In contrast to this, the conventional variable optical attenuator that has a plurality of Mach-Zehnder interferometers connected in series requires an electrical power of 1 W or more and has a response speed of tens of milliseconds, and has dimensions of 40 mm in width  $\times$  60 mm in length or

greater.

Figures 5A and 5B show another embodiment of an optical device of the present invention, in which Fig. 5A is a plan view and Fig. 5B is a sectional view taken along line VB-VB shown in Fig. 5A. The optical device comprises a 5 first optical attenuation portion 10 and a second optical attenuation portion 20, both of which are formed on a substrate 1.

The first optical attenuation portion 10 is a Mach-Zehnder interferometer, and comprises, at at least one of its arms, a variable optical attenuation means, that is, a heater, which changes the amount of attenuation 10 of signal light by producing a thermal phase shift. The second optical attenuation portion 20 comprises a groove 4 that traverses a core of a linear waveguide 11 disposed at an exit side of the first optical attenuation portion 10, an optical element 5 which is held inside the groove 4 and which has a plurality of optical attenuation elements exhibiting discretely differing light 15 attenuation amounts, and an actuation function portion 6 which moves the optical element 5 along the groove 4.

but can continuously adjust the optical attenuation amount. On the other hand, the second optical attenuation portion 20 cannot continuously adjust the 20 optical attenuation amount, but has a wide adjustment range. In a range in which the optical attenuation amount is from 0 to 10 dB or less, the amount of optical attenuation is adjusted only by the first optical attenuation portion 10. In a range in which the optical attenuation amount is from 10 dB to 40 dB or

greater, the second optical attenuation portion 20 and the first optical attenuation portion 10 are used in combination for continuous adjustment of the amount of optical attenuation over the entire range.

An optical attenuation element that essentially performs a intercepting 5 operation against signal light may be mounted as a portion of the optical element 5. When this is done, it is possible to realize an optical device which has both an optical attenuating function and a light-intercepting function, which has not been possible with conventional Mach-Zehnder variable optical attenuators. Here, the phrase "essentially performs a intercepting operation 10 against signal light" means that the optical attenuation amount is equal to or greater than 50 dB, so in such a case, only signal light power of a level insufficient for allowing light reception is transmitted.

The optical element 5 used in this embodiment may be formed of a dielectric multi-layer film or a metallic thin film as illustrated in Fig. 4, or 15 may be one that makes use of absorption or scattering of signal light. As shown in Fig. 6A, a circular optical element having different optical

Fig. 6B, a very small lens 52 may be used and moved in the direction of propagation of light or in a direction perpendicular thereto.

20 Here, it is important to make the amount of reflected returning light small in an area in which the optical attenuation amount is large. This is because, when the amount of reflected returning light is large, laser oscillation used to transmit signal light becomes unstable, and the S/N ratio of other

waveguides becomes small. In order to make the amount of reflected returning light small, a light-receiving surface of the optical element is processed to have a bumpy form by micro-machining, so that reflection and scattering occur in the directions different from a light-incident direction; or 5 the material used for the light-receiving surface may be one having high light absorptivity, so that the reflectivity of the light becomes equal to or less than 20 dB. Suitable materials having high absorptivity include organic materials and ceramic.

[Example 1]

10 A description of a specific example will be given with reference to Figs. 5A and 5B. A substrate 1 was made of silicon. After a lower clad layer 3-1 (film thickness: 20  $\mu\text{m}$ ) and a core layer (film thickness: 7  $\mu\text{m}$ ) were formed by depositing silica glass on the silicon substrate, the core layer was subjected to micro-machining to form a core 2. Then, an upper clad layer 3-2 (film 15 thickness: 30  $\mu\text{m}$ ) was formed thereupon by deposition so as to cover the core 2. After a thin chromium film (film thickness: 1  $\mu\text{m}$ ) was formed by vapor-

which was shaped such as to cover one of the arms of a Mach-Zehnder interferometer, so that a first optical attenuation portion 10 comprising an 20 optical circuit 12 and a heater 9 was formed.

Then, using a dicer, a groove 4 having a width of 50  $\mu\text{m}$  and a depth of 100  $\mu\text{m}$  was formed across a linear waveguide 11 at the exit side of the Mach-Zehnder interferometer so as to traverse the core. A small optical element 5 is

disposed inside the groove 4. At the same time, an actuation function portion 6, which moves the optical element 5 along the groove 4, was attached to the substrate 1 by securing portions 8, and the actuation portions thereof and the optical element 5 were joined through a supporting portion 7. Optical 5 attenuation elements were mounted to a light-receiving surface 5-1 of the optical element 5 on which signal light is incident. Figure. 7 is an enlarged view of an optical attenuation portion 30. Optical attenuation elements 30-1 to 10 30-8 having discretely differing optical attenuation functions of approximately 0 dB, 5 dB, 10 dB, 15 dB, 20 dB, 25 dB, 30 dB, and 35 dB were arranged in a row. These optical attenuation elements used in this example were formed of dielectric multi-layer films ( $\text{SiO}_2\text{-TiO}_2$  laminated films), and the light attenuation amounts were adjusted by the thicknesses of the multi-layer films and the number of layers used.

Figure 8 shows in detail an actuation function portion used in Example 15 1. The actuation function portion 6 comprises actuation portions 100A and 100B, formed on the surface of the substrate 1, with the groove 4 being located

comb-shaped electrode 110 and a second comb-shaped electrode 120, provided 20 on the surface of the substrate 1 so as to oppose each other, and a floating part 130, disposed between these corresponding electrodes 110 and 120 and having a portion thereof separated from the substrate 1.

Each floating part 130 comprises a comb-shaped floating electrode 130a, a base 130c which is directly formed on the surface of the substrate 1, and a

plate spring 130b. Each plate spring 130b connects the corresponding comb-shaped floating electrode 130a and the corresponding base 130c, and supports the corresponding comb-shaped floating electrode 130a so that it is away from the surface of the substrate 1 by a predetermined distance. Each comb-shaped floating electrode 130a is provided on both sides of a corresponding comb stem 115 which is provided so as to extend from the corresponding plate spring 130b, so that it does not contact adjacent comb teeth of the corresponding first comb-shaped electrode 110 and the corresponding second comb-shaped electrode 120. The supporting portion 7, to which the optical element 5 is attached, is supported by the floating parts 130 of the corresponding actuation portions 100A and 100B so as to cover a portion of the groove 4.

When a voltage is impressed between each first comb-shaped electrode 110 and its corresponding comb-shaped floating electrode 130a, each comb-shaped floating electrode 130a moves in the direction of arrow S1 accordingly as a result of being pulled by electrostatic force by the corresponding first comb-shaped electrode 110. At the same time, the supporting portion 7 and

thereto. Similarly, when a voltage is impressed between each second comb-shaped electrode 120 and its corresponding comb-shaped floating electrode 130a, the optical element 5 moves in a direction opposite the direction of arrow S1. In this way, by controlling the voltage applied to each of the first comb-shaped electrodes 110 or to each of the second comb-shaped electrodes 120 and its corresponding comb-shaped floating electrode 130a, it is possible to move

the optical element 5 by a predetermined amount along the groove 4.

Here, each floating part 130 was formed by a combination of photolithography and reactive ion etching (RIE). This is disclosed in detail in, for example, Applied Physics (vol. 60, No. 3, 1991, pp. 228 to 232), Silicon 5 Micromachining High Technology (Science Forum, March, 1992), and Silicon Micromachining and Micro Mechatronics (Baifukan, June, 1992).

It is possible to continuously change the optical attenuation function over the entire optical attenuation amount range of 0 dB to 40 dB by interlocking the first optical attenuation portion 10 having an optical 10 attenuation function continuously variable in the range of 0 dB to 5 dB and the second optical actuation portion 20 using an optical element and having an optical attenuation function discretely variable with every 5 dB step in the range of 0 dB to 35 dB.

Data regarding the relationship between the optical attenuation amount 15 and PDL obtained in this example are shown in Fig. 9. Since the birefringence of the optical element itself was small, the optical attenuation amount was of a

0.2 dB, so that excellent performance was achieved.

#### [Example 2]

20 Figures 10A and 10B show an optical device of Example 2, in which Fig. 10A is a plan view and Fig. 10B is a sectional view taken along line XB-XB shown in Fig. 10A. As in Fig. 5, a first attenuation portion 10 including a Mach-Zehnder interferometer optical circuit 12 and a heater 9 was formed.

Using a dicer, a groove 4' having a width of 80  $\mu\text{m}$  and a depth of 100  $\mu\text{m}$  was carved across a linear waveguide 11 at the exit side of the Mach-Zehnder interferometer so as to traverse a core. An actuator function portion 6' was provided near the groove 4', and an optical element 5' having a light-intercepting function was disposed inside the groove 4'.  
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The optical element 5' was moved into and out of the groove 4' by making use of electrostrictive strain (described later). When an end of the actuation function portion 6' was displaced downward in order to place the optical element 5' inside the groove 4', a intercepting operation was performed  
10 by the optical element 5' against signal light. On the other hand, when the end of the actuation function portion 6' was displaced upward in order to place the optical element 5' out of the groove 4', the signal light that had propagated inside the core virtually did not diffract in the groove, but propagated into the opposing core.

15 Figures 11A and 11B show an optical element used in the second example, in which Fig. 11A is a sectional view and Fig. 11B is an end view of

surface of the optical element 5' was processed to have a bumpy form such that a large portion of reflected returning light was prevented from going back to  
20 the optical circuit. The optical element 5' was formed by etching the surface of a silicon wafer into a bumpy form, and, then, cutting this into the shape of the optical element 5'.

The actuation function portion 6' includes an insulation layer 210

supporting the optical element 5', and electrodes 220a and 220b, sandwiching the insulation layer 210. When a predetermined voltage was not impressed between the electrodes 220a and 220b, the insulation layer 210 was set in a curved state as shown by the solid line in the drawing so that the optical 5 element 5' was outside the groove 4'. When a predetermined voltage is impressed between the electrodes, the insulation layer 210 moves in the direction of arrow S2 in the drawing such that the optical element 5' is disposed inside the groove 4'. Here, the insulation layer 210 and the electrodes 220a and 220b were fabricated by micromachining polysilicon films 10 and chromium metallic films by using photolithography and etching technologies.

When the optical attenuation amount is to be 0 dB to 10 dB, the optical element 5' is positioned outside the groove 4' in order to adjust the optical attenuation amount by the first optical attenuation portion 10. When a light 15 intercepting operation is to be performed, the optical element 5' is moved into the groove 4' in order to realize a light intercepting state in which the optical

state, the reflection attenuation amount is less than - 60 dB (lower limit of measurement). Driving power for moving the optical element 5' is 0.3 W, and 20 the response speed is about 0.1 ms.

In the two examples, while the substrates are described as being made of silicon, they may be made of silica glass, compound glass, or alumina or other ceramic materials. In the two examples, while the optical circuits are

described as being made of silica glass, they may be formed of semiconductor materials or polymer materials.

Although, in the foregoing description, a structure including one optical-circuit-type variable optical attenuation portion formed at a substrate, and one optical element having an optical attenuating function is described, a structure which uses two or more optical elements arranged in series at one optical-circuit-type variable optical attenuation portion may be used. The place where any of the optical elements is disposed may be at an exit-side optical circuit portion of the optical-circuit-type variable optical attenuation portion or at an entrance-side optical circuit portion thereof. In addition, the optical devices that have been described may be disposed parallel to each other on the same substrate. Such a structure is more suitable for handling multichannel signal light all at once in WDM communication.

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